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An approach for exhaust gas energy recovery of internal combustion engine: Steam-assisted turbocharging

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ABSTRACT

An approach for IC engine exhaust gas energy recovery, named as steam-assisted turbocharging (SAT), is developed to assist the exhaust turbocharger. A steam generating plant is coupled to the exhaust turbocharged engine's exhaust pipe, which uses the high-temperature exhaust gas to generate steam. The steam is injected into turbine inlet and used as the supplementary working medium for turbine. By this means, turbine output power and then boosting pressure can be promoted due to the increase of turbine working medium. To reveal the advantages and energy saving potentials of SAT, this concept was applied to an exhaust turbocharging engine, and a parameter analysis was carried out. Research results show that, SAT can effectively promote the low-speed performances of IC engine, and make the peak torque shift to low-speed area. At 1500 r/min, the intake gas pressure can reach the desired value and the torque can be increased by 25.0% over the exhaust turbocharging engine, while the pumping mean effective pressure (PMEP) and thermal efficiency only have a slight increase. At 1000 r/min, the improvement of IC engine performances is very limited due to the low exhaust gas energy.

1. Introduction

It is well known that exhaust turbocharging can effectively improve the internal combustion (IC) engine working load and downsize the displacement without decreasing its power performances [1,2]. In this way, it can ensure that IC engine often operates in the high efficiency area, and achieve the goals of IC engine energy conservation. For example, the 1.4 L TSI turbocharged engine made by Volkswagen Company, has better performances than the 2.3 L naturally-aspirated (NA) engine in many aspects. Compared with the NA engine, the displacement of TSI turbocharged engine is reduced by 39%, while the fuel consumption and CO_2 emission are reduced by 20% [3]. Therefore, exhaust turbocharging becomes a key technology and important approach for energy saving and emission reduction on IC engine [4].

Additionally, waste heat recovery (WHR) is another effective way for IC engine energy saving and CO_2 emission reduction [5–7]. So far, various kinds of approaches and technologies were proposed for IC engine WHR, and much attention focuses on this aspect [8]. For instance, Shu et al. [9] have conducted the performance comparison and working fluid analysis of subcritical and transcritical dual-loop organic Rankine cycle (DORC) used in engine WHR. Katsanos et al. [10] have carried on a thermodynamic analysis of a Rankine cycle applied on a diesel truck engine using steam and organic medium. They found that the brake specific fuel consumption improvement ranges from 10.2% (at 25% engine load) to 8.5% (at 100% engine load) for R245ca and from 6.1% (at 25% engine load) to 7.5% (at 100% engine load) for water. In reality, exhaust turbocharging is one of the most common means for IC engine exhaust gas energy recovery (EER) [11,12], since it uses exhaust gas energy to drive the compressor. As the energy source of turbocharging system and also the working medium of turbine, exhaust gas plays a very important role in the working performances of exhaust turbocharging system and IC engine. For example, the mass flow rate, pressure and temperature of exhaust gas determine the output power of turbine, and then influence the IC engine boosting pressure. Since the boosting pressure dominates the fresh charge and even the pumping process work of IC engine, it finally influences the performances of IC engine.

In the traditional exhaust turbocharging system, the mass flow rate of exhaust gas equals to the sum of intake gas and fuel mass flow rate, and it approximately grows in linear with the increase of IC engine speed. As a result, different speed corresponds to

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Nomenclature

P	power (kW)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (kPa) (MPa)
ρ	density (kg/m^3)
η	efficiency
c_P	constant pressure specific heat (kJ/(kg K))
T	temperature (K)
γ	specific heat ratio
V_s	displacement (l)
n	speed (r/min)
i	cylinder number
τ	stroke number
B	consumption of fuel (kg/h)
H_u	low heating value (kJ/kg)
ε	improvement rate

Subscripts

pum	pump
ste	steam
tur	turbine
exh	exhaust
mix	mixture
com	compressor
int	intake
tra	transmission shaft
ice	internal combustion engine
me	brake mean effective pressure
the	thermal efficiency
tor	torque

Abbreviation

SAT	steam-assisted turbocharging
ET	exhaust turbocharging
IC	internal combustion
WHR	waste heat recovery
DORC	dual-loop organic Rankine cycle
EER	exhaust gas energy recovery
EAT	electric assisted turbocharging
BMEP	brake mean effective pressure
PMEP	pump mean effective pressure
AFR	air/fuel ratio
NA	naturally aspirated

different exhaust gas mass flow rate, and the change of exhaust gas mass flow rate results in the variation of turbine performances. Generally, under the high-speed operating conditions, since the mass flow rate of IC engine exhaust gas is too large, part of exhaust gas should be bypassed via the waste gate [13]. While under the low-speed operating conditions, the mass flow rate of IC engine exhaust gas is very small. In the meantime, the exhaust gas pressure is also very low, and both of the two aspects lead to a small turbine output power. Under the circumstances, the turbine output power is lower than the required compressor power thus intake gas pressure cannot achieve the desired level. Accordingly, it leads to the consequence that the IC engine torque as well as the power is lower than the expected level. Furthermore, IC engine has bad fuel efficiency and emission performance at the low-speed operating conditions. Consequently, improving the low-speed performances of exhaust turbocharging engine is the goal pursued by many scientists and engineers. To achieve this goal, some approaches were proposed in the past, e.g., two-stage turbocharging [14] and electric assisted turbocharging (EAT). It is true that these approaches can effectively promote the low-speed performances of exhaust turbocharging engine, but IC engine total energy efficiency (or thermal efficiency) is influenced because some additional power is consumed.

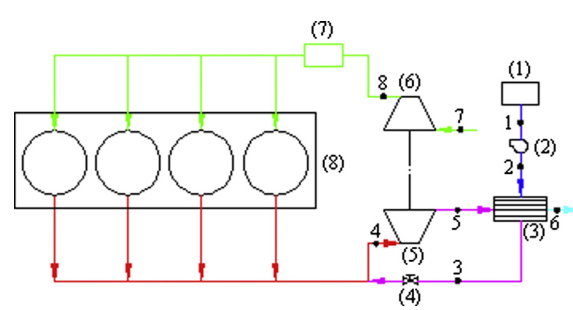
To solve the problems mentioned above, a novel concept of SAT was proposed to improve the performances of traditional IC engine exhaust turbocharging, which is also a kind of novel approach for IC engine exhaust gas energy recovery [15]. In the previous study, the authors only proposed the concept of SAT, and compared the performances of exhaust turbocharging, steam turbocharging and SAT engine [15]. Being different from the previous study, in this research, the detailed working processes of SAT system were analyzed and the calculation method for SAT engine was developed. Also, a numerical calculation and parameter analysis was conducted on the SAT system as well as the SAT engine. On this basis, the performances of SAT engine and exhaust turbocharged engine were compared for the purpose of demonstrating the superiority and feasibility of SAT system. In addition, the overall improvements to torque and thermal efficiency of SAT engine have been compared to previous studies [15].

2. Description of steam-assisted turbocharging

2.1. Concept of steam-assisted turbocharging

The schematic diagram of proposed SAT system is depicted in Fig. 1. Combining with this schematic diagram, the working principle of SAT is introduced. In the exhaust turbocharging engine, a set of steam generating plant, which includes water tank, pump, heat exchanger, valve, etc., is coupled to the IC engine exhaust pipe to produce steam. In the steam generating plant, the working medium water is heated into superheated steam by the high-temperature exhaust gas of IC engine in heat exchanger. Then, the superheated steam is injected into the turbine inlet and used as the compensatory working medium for the turbine. By this means, the turbine output power can be improved due to the increase of working medium. As a result, the intake gas pressure increases and then the IC engine power performances can also be promoted.

According to what is described above, the SAT system follows the principle of open steam power cycle [16]. Similar to the exhaust turbocharging, it is a kind of approach for IC engine exhaust gas energy recovery. Nevertheless, being different from



(1) Water tank (2) Pump (3) Heat exchanger (4) Valve
(5) Turbine (6) Compressor (7) Intercooler (8) IC engine

Fig. 1. Schematic diagram for SAT system.

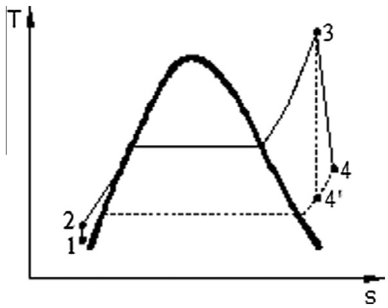


Fig. 2. T-s diagram for SAT bottom cycle.

other approaches, e.g., Rankine bottom cycle [17–20], Brayton air cycle [11,21] and turbocompounding [22], the recovered exhaust gas energy in SAT system is used to assist the turbine without net output work.

The corresponding thermodynamic processes of SAT are depicted in Fig. 2. According to the T-s diagram, the working processes of thermodynamic cycle are described. Firstly, working medium water is compressed to a certain pressure in the pump, as shown in process 1–2. As water's compressibility is very small, very little work is consumed during the compression process. Then, the high-pressure water is directed into the heat exchanger, in which it is first evaporated and then superheated by the high-temperature exhaust gas of IC engine, as illustrated in process 2–3. After that, the superheated steam is injected into the turbine inlet, in which it mixes with IC engine exhaust gas and then expands in the turbine. In the T-s diagram, process 3–4′ represents the isentropic expansion, and process 3–4 indicates the actual expansion.

In the SAT system, IC engine exhaust gas energy is recovered twice. First, part of exhaust gas energy is directly recovered by turbine through exhaust gas expanding. Since the expansion ratio of turbine is not large enough, exhaust gas temperature at the turbine outlet is still very high. As a result, the exhaust gas at turbine outlet still has a spate of energy, which is recovered again by heat exchanger through a complex thermodynamic cycle. In this thermodynamic cycle, exhaust gas energy is first turned into the enthalpy of steam, and then it is converted into the effective work of turbine. In a word, SAT system merges the advantages of both the direct recovery method and indirect recovery method of exhaust gas energy. In this way, more exhaust gas energy can be recovered, and the utilization efficiency of exhaust gas energy can be improved.

2.2. Characteristics of steam-assisted turbocharging

As introduced previously, the exhaust turbocharging and Rankine steam cycle are combined together in this SAT system. In other words, the SAT system is a kind of revised approach of IC engine exhaust turbocharging. Consequently, it also has the characteristics of exhaust turbocharging. Compared with the traditional exhaust turbocharging, the differences in SAT system could be summarized as follows: (1) Since the working medium flow rate of turbine can be adjusted by injecting steam, SAT has better controllability and working performances. In the traditional exhaust turbocharging system, turbine working performances only associate with IC engine exhaust gas parameters. Under most of IC engine operating conditions, turbine's operating points are out of the optimal area (high efficiency area). However, in the SAT system, working medium mass flow rate of turbine can be optimized by changing the steam amount. As a result, turbine's output power can be boosted to a desired level, and the intake gas pressure as well as IC engine power performances, e.g., torque, can also be improved. (2) In the SAT system, the energy comes from IC engine exhaust gas rather than other mechanical energy or electric energy, since the SAT is a kind of means for IC engine exhaust gas energy recovery. As a result, it is more useful to promote the energy utilization efficiency of IC engine than other assisted technologies for turbocharging, such as EAT. (3) By real-time controlling the injection time and injection amount of steam, SAT system could have a better transient response performance. Accordingly, the acceleration performance of automobile (or IC engine) can be promoted. (4) In addition, through recovering the exhaust gas energy, IC engine exhaust gas temperature can be reduced, which is beneficial to decrease the thermal stress and aerodynamic noise of exhaust system. As anything has two sides, the SAT system also brings some negative effects to the IC engine. For instance, the added SAT system results in the increase of cost, and the increased humidity of exhaust gas due to the injected steam may corrode the turbine blades. All these issues will be studied in the future.

2.3. Calculation formulas for steam-assisted turbocharging

Combining with the T-s diagram of SAT bottom cycle, the cycle processes are analyzed and the calculation formulas for SAT system are given. Firstly, the compression power consumed by pump could be calculated as

$$P_{pum} = \frac{p_2 - p_1}{\rho_1} \cdot \frac{\dot{m}_{ste}}{\eta_{pum}} \tag{1}$$

where P_{pum} is the compression power consumed by pump; $\dot{m}_{ste}$ is the mass flow rate of steam (or water); p_1 and p_2 are the pressure of working medium water at the inlet and outlet of pump, respectively; ρ_1 is the density of working medium water at the pump inlet; η_{pum} is the isentropic efficiency of pump.

In the SAT system, turbine is the power output equipment, and its working medium is the mixture gas of IC engine exhaust gas and injected steam. During the expansion process of mixture gas, the effective power is generated. The calculation formula for turbine output power is given as

$$P_{tur} = (\dot{m}_{exh} + \dot{m}_{ste}) \cdot c_{P,mix} \cdot T_4 \cdot \left(1 - \left(\frac{p_5}{p_4}\right)^{\frac{\gamma_1 - 1}{\gamma_1}}\right) \cdot \eta_{tur} \tag{2}$$

where P_{tur} is the output power of turbine; $\dot{m}_{exh}$ is the mass flow rate of IC engine exhaust gas; $\dot{m}_{ste}$ is the mass flow rate of steam; $c_{P,mix}$ is the constant-pressure specific heat of mixture gas at the turbine inlet; T_4 is the temperature of mixture gas at the turbine inlet; p_4 and p_5 are the pressure of mixture gas at the inlet and outlet of turbine, respectively; γ_1 is the specific heat ratio of mixture gas; η_{tur} is the isentropic efficiency of turbine.

Accordingly, the relationship between the required compressor power and intake gas pressure (boosting pressure) is given as

$$\begin{aligned} P_{com} &= \dot{m}_{int} \cdot c_{P,int} \cdot (T_8 - T_7) \\ &= \dot{m}_{int} \cdot c_{P,int} \cdot T_7 \cdot \left[\left(\frac{p_8}{p_7}\right)^{\frac{\gamma_2 - 1}{\gamma_2}} - 1\right] \cdot \frac{1}{\eta_{com}} \end{aligned} \tag{3}$$

$$P_{com} = P_{tur} \cdot \eta_{tra} \tag{4}$$

where P_{com} is the required compressor power; $\dot{m}_{int}$ is the mass flow rate of intake gas; $c_{P,int}$ is the constant-pressure specific heat of intake gas; T_7 and T_8 are the intake gas temperature at the inlet and outlet of compressor, respectively; p_7 and p_8 are the intake gas pressure at the inlet and outlet of compressor, respectively; γ_2 is the specific heat ratio of intake gas; η_{com} is the isentropic

efficiency of compressor, η_{tra} is the mechanical efficiency of transmission shaft.

Next, the calculation formulas for IC engine performance parameters are also given. The effective power of IC engine can be calculated via [13]

$$P_{ice} = \frac{p_{me} \cdot V_s \cdot n \cdot i}{30\tau} \quad (5)$$

where P_{ice} is the effective power of IC engine; p_{me} is the brake mean effective pressure (BMEP) of IC engine; V_s is the displacement of each cylinder; n is the IC engine speed; i is the cylinder number; τ is the stroke number.

And the torque of IC engine can be calculated via [13]

$$T_{ice} = \frac{318.3p_{me} \cdot V_s \cdot i}{\tau} \quad (6)$$

where T_{ice} is the torque of IC engine.

At the same time, the calculation formula for IC engine effective thermal efficiency is given as

$$\eta_{ice} = \frac{3.6 \times 10^3 P_{ice}}{B \cdot H_u} \quad (7)$$

where η_{ice} is the effective thermal efficiency of IC engine; B is the consumption of fuel in per hour; H_u is the low heating value of fuel.

In order to better evaluate the energy-saving potential of SAT engine, the improvement of SAT engine thermal efficiency is defined as

$$\eta_{imp} = \eta_{SAT} - \eta_{ET} \quad (8)$$

where the η_{imp} is the improvement of SAT engine thermal efficiency; η_{SAT} is the thermal efficiency of SAT engine; η_{ET} is the thermal efficiency of exhaust turbocharging (ET) engine.

For the purpose of comparing the improvements of various performance parameters between different IC engines with different boundary conditions, the improvement rate is defined. In this study, only the improvement rates of thermal efficiency and torque are discussed, whose calculation formulas are given as follows

$$\varepsilon_{the} = \frac{\eta_{SAT} - \eta_{ET}}{\eta_{ET}} \cdot 100\% \quad (9)$$

$$\varepsilon_{tor} = \frac{T_{SAT} - T_{ET}}{T_{ET}} \cdot 100\% \quad (10)$$

where ε_{the} is the improvement rate of IC engine thermal efficiency; ε_{tor} is the improvement rate of IC engine torque; T_{SAT} is the torque of SAT engine; T_{ET} is the torque of ET engine.

3. Calculation processes

3.1. Calculation and analysis of exhaust turbocharging engine

To reveal the effects of SAT system on IC engine performances, the concept of SAT is applied to an ET engine, and the method of numerical simulation is used for this investigation. First of all, the performances of exhaust turbocharging engine were simulated and analyzed, thus the results can be used as the comparison baseline for SAT engine. The research object in this paper is an exhaust turbocharged gasoline engine, the basic parameters and specifications of which are listed in Table 1. According to the geometric structure parameters and pipeline layout as well as performance data of this gasoline engine, the corresponding GT-power simulation model was built and calibrated, as shown in Fig. 3.

In this simulation model, the boundary conditions of its inlet and outlet, such as ambient pressure and temperature, were set to the standard atmospheric state. The remaining parameters, e.g., mechanical friction loss, combustion efficiency and air/fuel ratio, were calibrated by the test data of this IC engine. Among them, the flow coefficients of intake and exhaust valve were acquired by airway test. The resistance coefficient and heat transfer coefficient of pipe wall were obtained through looking-up the tables of material properties. In this research, only the full load operating conditions were considered, and the reason can be explained as follows. At IC engine part load, the required power and torque is relatively low. Accordingly, the IC engine (without SAT) can provide the corresponding power and torque to meet the requirement, at the same time, intake gas throttling is applied to limit or adjust the IC engine power (or torque). Under the circumstances, there is no practical significance to apply the method of SAT at part load, since the IC engine exhaust gas flow rate and turbine output power are large enough to generate a desired boosting pressure (In fact, at low-speed and low-load, the required boosting pressure is very low and there is even no need for turbocharging). Since the content of this study is largely based on numerical simulation, a figure comparing measured and calculated data of the IC engine is necessary to demonstrate its reliability. As two of the representative parameters for IC engine performances, the IC engine BMEP and intake mass flow rate are compared in Fig. 4(a) and (b), respectively. As shown, Fig. 4(a) displays the measured and calculated results of IC engine BMEP, and Fig. 4(b) gives the measured and calculated data of IC engine intake mass flow rate. The comparison results show good agreement with the measured data and calculated data, so it demonstrates that the simulation model has enough precision to simulate the work process of this IC engine.

Table 1
The basic parameters of gasoline engine.

Item	Content
Engine type	Inline four cylinder
Bore (mm)	80
Stroke (mm)	89.3
Displacement (l)	1.796
Compression ratio	9.2
Ignition mode	1-3-4-2
Intake mode	Turbocharging
Cooling type	Water-cooling
Rated power (kW/rpm)	118/5500
Maximum torque (Nm/rpm)	215/2000–4500

Based on the numerical simulation, the performances of exhaust turbocharging engine were calculated at full load. Fig. 5 shows the results of torque and volumetric efficiency of the exhaust turbocharging engine. As can be seen from this figure, the torque of exhaust turbocharging engine is very low in the low-speed area of 1000–2000 r/min. However, when the speed is higher than 2500 r/min, it increases to a desired value and then almost keeps a constant except the high speed. For a gasoline engine, the torque mainly depends on the volumetric efficiency since the AFR changes a little in the entire speed area [23]. And it can also explain the phenomenon that the curve profile of torque is similar with that of volumetric efficiency. At the same time, a conclusion can be drawn that the low torque at low-speed is caused by the poor volumetric efficiency. It is well known that the volumetric efficiency of IC engine is largely influenced by the intake gas pressure [23]. Fig. 6 gives the pressure and mass flow rate of intake gas at the compressor outlet. As the figure shows, when the IC engine speed is higher than 2500 r/min, intake gas pressure reaches a high level (it is higher than 1.55 bar). However, when the IC engine speed is lower than 2000 r/min, intake gas pressure is far from the desired value. To be precise, the lower the speed is, the lower the intake gas pressure will be. As a result, the mass flow rate of intake gas is limited by the low intake gas pressure. According to the working principle of exhaust

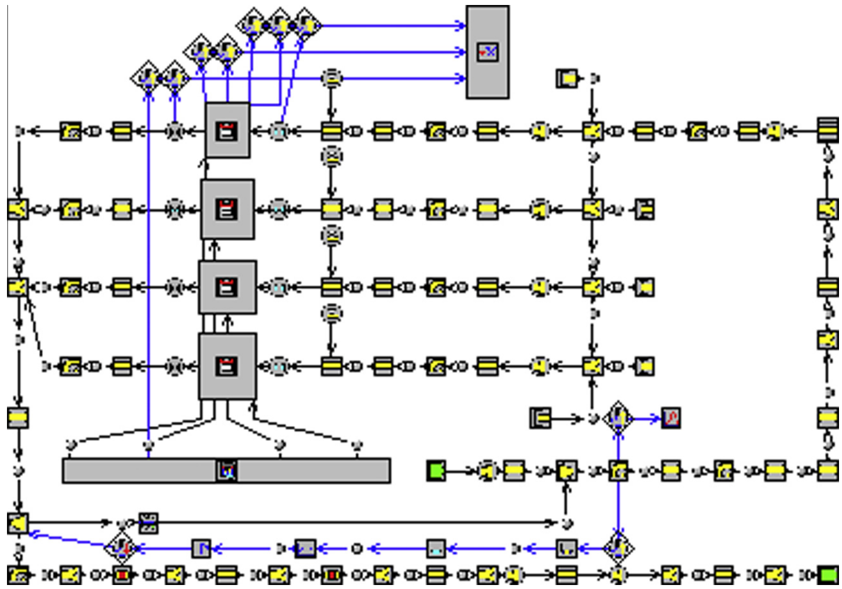
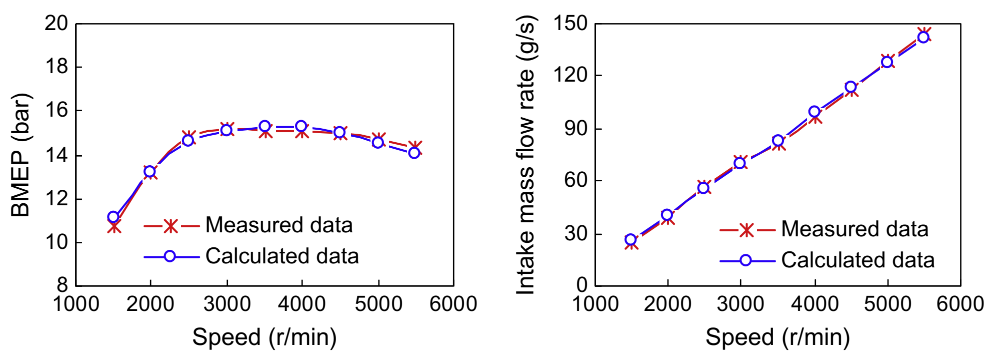


Fig. 3. Numerical model of exhaust turbocharging engine in GT-power.



(a) BMEP of IC engine (b) Intake mass flow rate of IC engine

Fig. 4. Comparison of measured and calculated data of IC engine (at full load).

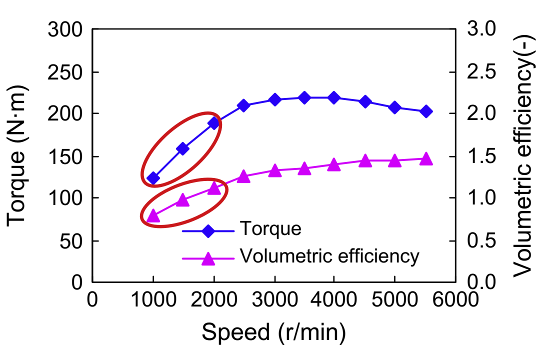


Fig. 5. Torque and volumetric efficiency of ET engine.

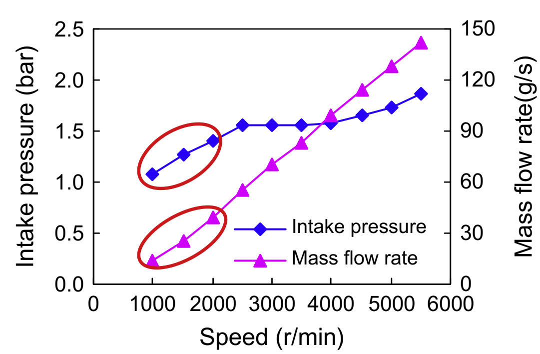


Fig. 6. Intake pressure and mass flow rate of ET engine (compressor outlet).

turbocharger, it can be known that the intake gas pressure is determined by the turbine output power. In accordance with Formula (2), the turbine output power is mainly dominated by the exhaust gas mass flow rate and exhaust gas pressure (turbine inlet pressure). Under the low-speed operating conditions, both exhaust gas mass flow rate and exhaust gas pressure are very low (as shown in Fig. 7), and it leads to the consequence that the output power of turbine is too little to provide an expected power for the compressor.

3.2. Calculation of SAT bottom cycle

Through the analysis on the performances of exhaust turbocharging engine, it can be found that exhaust turbocharging engine has poor performances under the low-speed operating conditions due to the low intake gas pressure. For the purpose of improving the low-speed performances of exhaust turbocharging engine, the concept of SAT is applied to this exhaust turbocharging engine. According to the former analysis, the boosting pressure cannot

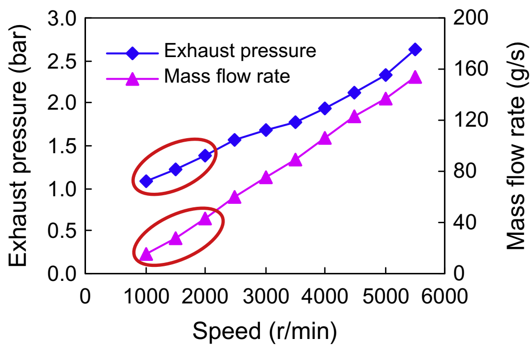


Fig. 7. Exhaust pressure and mass flow rate of ET engine (turbine inlet).

Table 2
Performance data of exhaust turbocharged engine.

Item	Content		
Speed (r/min)	1000	1500	2000
Power (kW)	12.9	25.0	39.5
Torque (N·m)	123.1	159.1	188.4
Exhaust temperature at turbine outlet (K)	901.8	934.3	977.3
Exhaust flow rate (g/s)	15.0	27.8	42.7
Turbine efficiency (%)	47.1	49.4	55.8
Turbine output power (kW)	0.21	1.03	2.02
Compressor efficiency (%)	41.1	53.3	60.2

reach the desired value when the speed is lower than 2000 r/min. In this study, the speed points of 1000 r/min, 1500 r/min and 2000 r/min were investigated in detail. In these speed points, the target boosting pressure of intake gas is set to 1.55 bar, which is the same as the boosting pressure at most of other speed points. And the corresponding performance data of exhaust turbocharging engine as well as turbocharging system at these speed points are listed in Table 2, which are used as the boundary conditions of SAT system.

The calculation processes of SAT engine are given in Fig. 8. Firstly, based on the simulated results especially the exhaust gas parameters of exhaust turbocharging (ET) engine, the exhaust gas energy flow of ET engine was calculated. Then, the maximum steam amount produced by the exhaust gas energy of ET engine at various steam temperatures were obtained via energy-balance equation. In this calculation, the corresponding boundary conditions were given in Table 3. As shown, the exhaust temperature at heat exchanger outlet was assumed to be 473.15 K, and the initial water temperature at heat exchanger inlet was set to 298.15 K. During the heat transfer process, the heat exchanger effectiveness was designed to 0.98. It means that 98% of exhaust gas energy flowing into heat exchanger is used to heat water (or steam), and the remaining is wasted due to the heat loss. On this basis, the SAT system was conducted the first round calculation. Before this step, the boundary conditions for SAT system should be determined. The steam injection amount of SAT system was set according to the maximum steam amount generated by ET engine exhaust gas energy, and the steam injection pressure was assumed to be 5 bar, which was referred to the injection pressure of port-injected natural gas engine. During the calculation process, various kinds of steam injection amount (steam mass flow rate) and different steam temperature were considered. After simulating the working process of SAT engine, the mixture gas (exhaust gas and steam) parameters at turbine outlet, including the mixture gas temperature and mass flow rate, etc., could be acquired via numerical calculation. Then, the exhaust gas energy flow of SAT engine was calculated. After that, the effective range of steam mass flow rate in SAT system (or the maximum steam amount generated by

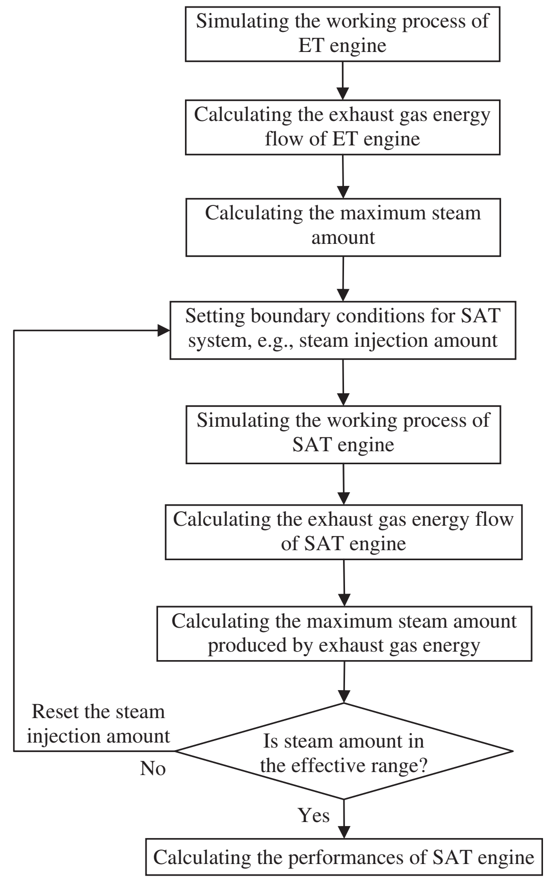


Fig. 8. The calculation processes of SAT engine.

Table 3
Boundary conditions and initial parameters of SAT bottom cycle.

Item	Content
Injection pressure of steam (bar)	5
Steam temperature (K)	500, 600, 700
Exhaust temperature at heat exchanger outlet (K)	473.15
Water temperature at heat exchanger inlet (K)	298.15
Heat exchanger effectiveness	0.98
IC engine speed (r/min)	1000, 1500, 2000
Mechanical efficiency of transmission shaft	0.98

the SAT engine exhaust gas energy) could be determined through energy-balance equation, which is similar to the calculation process of solving the maximum steam amount generated by the ET engine exhaust gas energy. Next, a judgment should be made. That is, if the steam injection amount (initial parameter) is less than the maximum steam amount generated by the SAT engine exhaust gas energy, we can consider that the calculation of SAT engine is valid (or converged), and the next step is executed to calculate the performances of SAT engine. Or else, the steam injection amount should be reset, and then the calculation for SAT system should be iterated for the second round, until the steam injection amount falls in the effective range of steam mass flow rate.

4. Results and discussions

4.1. Effects of bottom cycle parameters on the performances of SAT system

Above all, the effects of bottom cycle parameters on the performances of SAT system are discussed. In this section, the speed

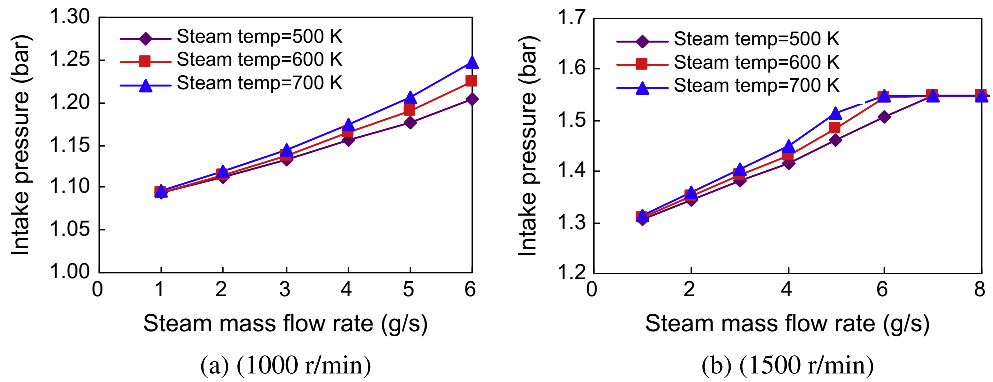


Fig. 9. Intake pressure vs. steam mass flow rate.

points of 1000 r/min and 1500 r/min are chosen as the representative cases and analyzed in detail. Fig. 9(a) and (b) show the intake gas pressure of SAT engine at the two kinds of speed, respectively. As can be seen from the two figures, with the increase of steam temperature and steam mass flow rate, SAT engine intake gas pressure rises gradually. At 1500 r/min, when the steam mass flow rate reaches a certain level, the intake gas pressure can achieve the target value of 1.55 bar. Then, a question comes out as how much steam could be produced by the SAT engine exhaust gas energy at most? At the same IC engine speed, the maximum steam mass flow rate at different steam temperatures changes a little. For example, at the same speed of 1000 r/min, when the steam temperature comes up to 500 K, 600 K and 700 K, the corresponding maximum steam mass flow rates (the steam could be produced by SAT engine exhaust gas energy) are 3.33 g/s, 3.30 g/s and 3.27 g/s, respectively, as shown in Table 4. This phenomenon can be analyzed as follows. On one hand, at each IC engine speed, the higher the steam temperature is, the more the exhaust gas energy will be required by the same steam. As a result, the less steam could be produced when the IC engine exhaust gas energy is constant. On the other hand, on the condition that the steam mass flow rate is fixed, higher steam temperature results in higher intake gas pressure and then more exhaust gas amount. Hence, more exhaust gas amount contributes to larger exhaust gas energy and then more steam could be generated. Due to the two kinds of factors, the maximum steam mass flow rate varies slightly with the steam temperature at each IC engine speed. Based on the analysis above, a conclusion can be drawn that it is better to select a higher steam temperature for the SAT engine since the maximum steam mass flow rate changes a little.

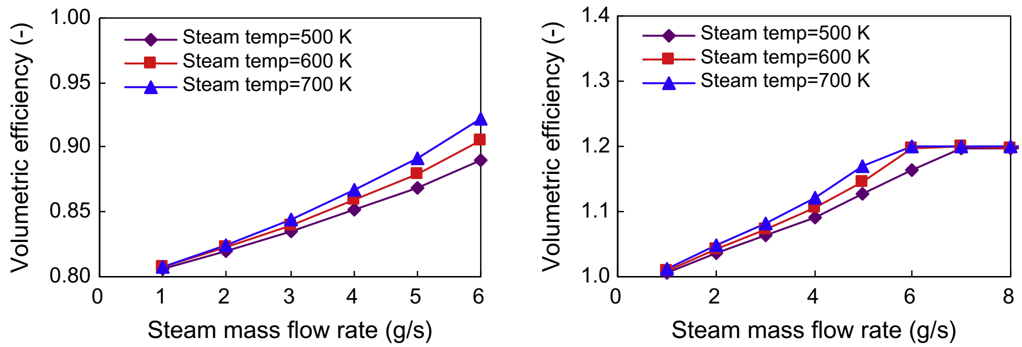
However, the highest steam temperature is limited by the exhaust gas temperature of SAT engine and the heat transfer process in heat exchanger (to be precise, the temperature difference of heat transfer). If the steam temperature is too low, the mixture gas (IC engine exhaust gas and steam) temperature will be decreased, and finally the output power of turbine will also be influenced. At the speed of 1000 r/min, as the maximum steam flow rate is too low, the effect of steam temperature on intake gas pressure is not very significant. And no matter what the steam temperature is, the intake gas pressure of SAT engine cannot reach the desired value. This is because the exhaust gas energy of SAT engine is too low to produce enough steam at this speed. However, things are changed at the speed of 1500 r/min. Under that circumstance, since the SAT engine exhaust gas energy increases a lot, more steam could be produced. As a result, both the intake gas pressure and maximum steam flow rate have a great ascension. At the same time, the effective range of steam mass flow rate also has a great augment. Fig. 10(a) and (b) show the relationship between the volumetric efficiency of SAT engine and the steam injection amount at the speed of 1000 r/min and 1500 r/min, respectively. On the condition that IC engine speed and other parameters are fixed, volumetric efficiency is almost proportional to the intake gas pressure. At 1000 r/min, the improvement of volumetric efficiency is very limited due to the low intake gas pressure. However, the volumetric efficiency has a sharp increase and can easily reach 1.2 at 1500 r/min.

As a key factor for turbine performance, the exhaust gas pressure (turbine inlet pressure) of SAT engine is discussed, and it is displayed in Fig. 11(a) and (b). As the two figures illustrate, the exhaust gas pressure almost increases in linear with the steam mass flow rate, and it is similar to the variation trend of IC engine intake gas pressure. Moreover, the higher the steam temperature is, the higher the exhaust gas pressure will be. The exhaust gas pressure has two kinds of effects on the IC engine performances. On one hand, a higher exhaust gas pressure corresponds to a higher expansion ratio of turbine, which is helpful to improve the turbine output power. On the other hand, the higher the exhaust gas pressure is, the more the effective work should be consumed for the exhaust process. However, the intake process work will also be boosted due to the increase of intake gas pressure. Finally, the pumping work of SAT engine changes a little.

As an important parameter to evaluate the turbine performance, the turbine efficiency of SAT engine is investigated, and it is depicted in Fig. 12(a) and (b). For a fixed turbine, its efficiency depends on the working medium parameters. More specifically, the turbine efficiency changes with the mass flow rate, pressure and temperature of working medium (exhaust gas). Through analyzing the turbine MAP, it can be found that the high efficiency operating points of turbine are located in the area of medium mass flow rate and medium expansion ratio. At the speed of 1000 r/min and 1500 r/min, the turbine efficiency of ET engine is very low due to the lack of exhaust gas flow rate and also the low expansion ratio. In the SAT engine, this issue can be solved by injecting steam into the turbine. As shown in Fig. 12(a) and (b), the turbine efficiency increases along with both steam mass flow rate and steam temperature. At the same time, the turbine output power is also concerned, which is given in Fig. 13(a) and (b). According to Formula (2), it is not difficult to find out that both the working

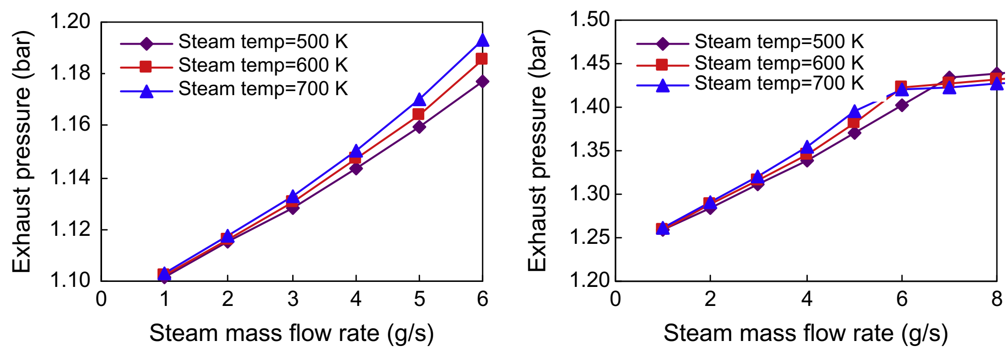
Table 4
The Max. steam amount generated by SAT engine exhaust gas energy.

IC engine speed (r/min)	Steam temperature (K)	Max. steam amount (g/s)
1000	500	3.33
	600	3.30
	700	3.27
1500	500	7.63
	600	7.52
	700	7.47



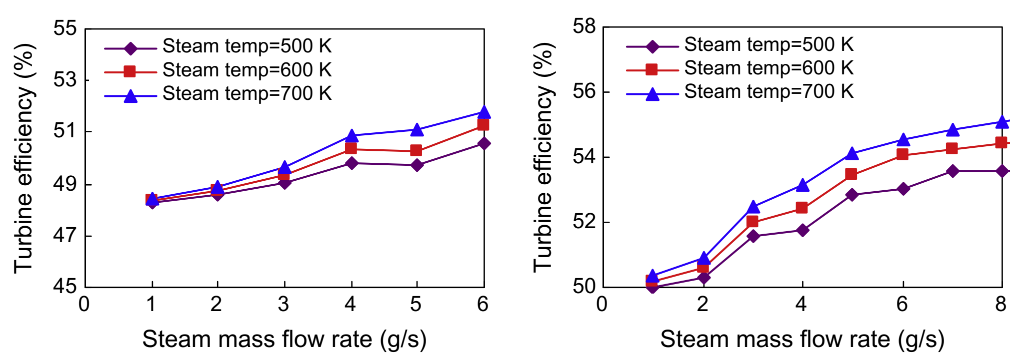
(a) (1000 r/min) (b) (1500 r/min)

Fig. 10. Volumetric efficiency vs. steam mass flow rate.



(a) (1000 r/min) (b) (1500 r/min)

Fig. 11. Exhaust gas pressure (turbine inlet) vs. steam mass flow rate.



(a) (1000 r/min) (b) (1500 r/min)

Fig. 12. Turbine efficiency vs. steam mass flow rate.

medium mass flow rate and turbine efficiency have important effects on the turbine output power. In the SAT engine, the steam injection amount not only influences the working medium mass flow rate of turbine, but also determines the turbine efficiency. In a word, the steam injection amount (steam mass flow rate) has dual effects on the turbine output power. As Fig. 13(b) shows, at 1500 r/min, when the steam mass flow rate increases from 1 g/s to 7 g/s (steam temperature is fixed at 700 K), the turbine output power can be promoted from 1.2 kW to 2.4 kW. Under the circumstances, the intake gas pressure and other performances of SAT engine can be improved significantly, all that will be discussed in the next section.

4.2. Performance improvement potentials of SAT engine

From the above analysis, it is not difficult to find that steam temperature plays an important role in the turbine output power, and a higher steam temperature contributes to a larger intake gas pressure. At different steam temperature, the maximum steam amount produced by SAT engine exhaust gas energy changes a little. According to this principle, the performance improvement potentials of SAT engine were studied, and three speed points, 1000 r/min, 1500 r/min and 2000 r/min were elaborated. In this research, the steam temperature was fixed to 700 K. At the case of 1000 r/min, the steam injection amount was set to the

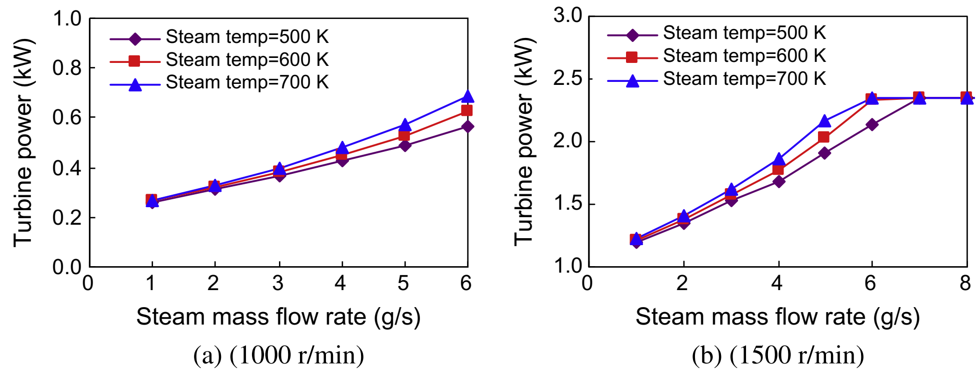


Fig. 13. Turbine output power vs. steam mass flow rate.

maximum steam amount produced by exhaust gas energy. While in the other two cases, the steam injection amount was dominated by the target boosting pressure. In the meantime, the calculation results of SAT engine were compared with ET engine for the purpose of revealing the performance improvement potentials of SAT engine. Fig. 14 shows the intake gas pressure of ET engine and SAT engine. As it displays, intake gas pressure of SAT engine can reach the desired value of 1.55 bar at 1500 r/min and 2000 r/min, while it is only 1.2 bar at 1000 r/min. Compared with the ET engine, the intake gas pressure of SAT engine is only increased by 0.1 bar at 1000 r/min. This is because the exhaust gas energy is too little to produce enough steam at this case. At the same time, the power performances of SAT engine, such as brake mean effective pressure (BMEP), torque and power, can be obviously promoted at these low-speed operating conditions. Fig. 15 displays the torque of SAT engine and ET engine. As it illustrates, the torque of SAT engine is largely improved at low-speed operating conditions. For example, the torque of SAT engine comes up to 198.7 N m at 1500 r/min, which is increased by 25.0% over the ET engine. All those demonstrate that SAT can effectively improve the power performances of IC engine at low-speed operating conditions.

As the power output component of SAT system, the working performances of turbine are discussed. Fig. 16 shows the turbine efficiency of the two kinds of IC engines. As illustrated, turbine efficiency of ET engine is very low at low-speed operating conditions. Since the turbine output power relies largely on the turbine efficiency, the low turbine efficiency corresponds to the small turbine output power, as shown in Fig. 17. After the steam is injected into the turbine inlet, the turbine working performances of SAT engine are changed. Because the mass flow rate of turbine working medium is increased, the turbine operating points shift to the high efficiency area. At the speed of 1000 r/min and 1500 r/min, the turbine efficiency of SAT engine can be increased by 2.9 and 5.7 percentage points, respectively. Accordingly, the turbine output power has a certain increase especially at 1500 r/min.

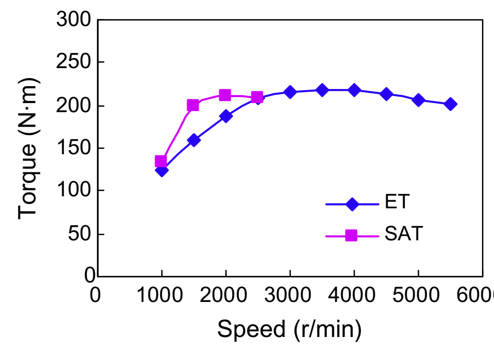


Fig. 15. Torque vs. IC engine speed.

One of the most concerns of this research is the energy saving potential of SAT system. So as to analyze this issue, the pumping work is discussed firstly since the gas exchange process of SAT engine is changed. As mentioned above, when the steam is injected into the exhaust pipe (turbine inlet), the exhaust gas pressure will be increased. As a result, more effective work is consumed during the exhaust process. However, the intake process work is also enhanced because of the increase of intake gas pressure. In this SAT engine, the intake process work is larger than the exhaust process work, thus the PMEP of SAT engine is higher than that of ET engine (as shown in Fig. 18), which is beneficial to promote the energy utilization efficiency of the former. Besides, according to the analysis of IC engine energy balance [24–26], the high thermal efficiency operating conditions usually appear in the high load (BMEP) area. Due to the increase of PMEP and BMEP (or torque),

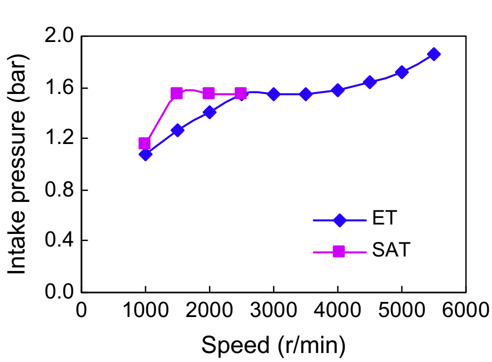


Fig. 14. Intake pressure vs. IC engine speed.

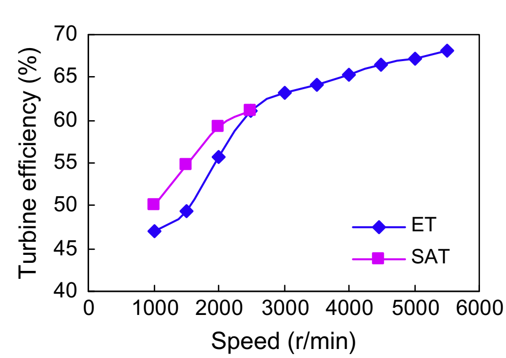


Fig. 16. Turbine efficiency vs. IC engine speed.

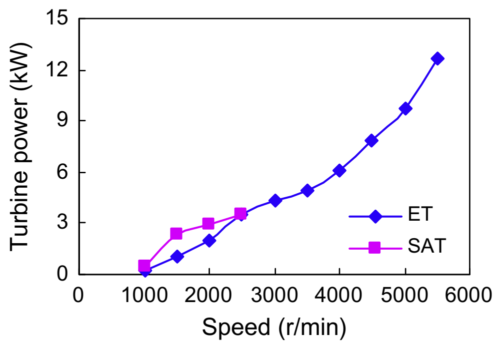


Fig. 17. Turbine output power vs. IC engine speed.

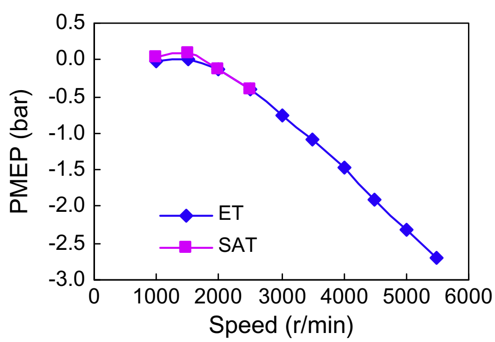


Fig. 18. PMEP vs. IC engine speed.

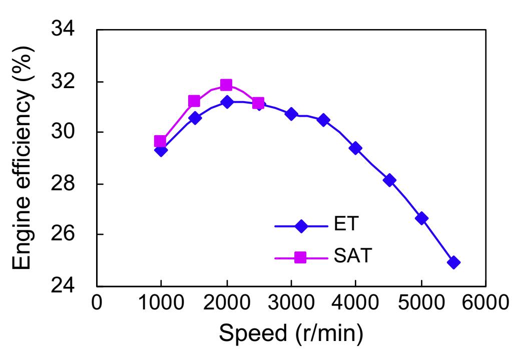


Fig. 19. Thermal efficiency vs. IC engine speed.

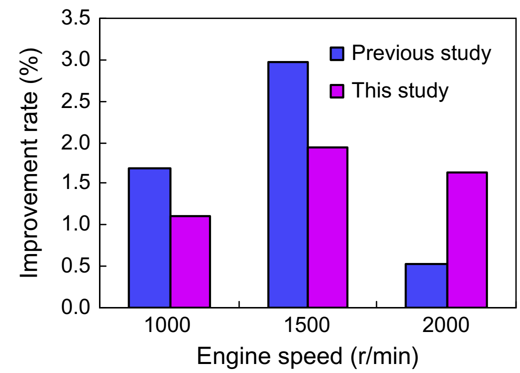


Fig. 20. Comparison of thermal efficiency improvement rate [15].

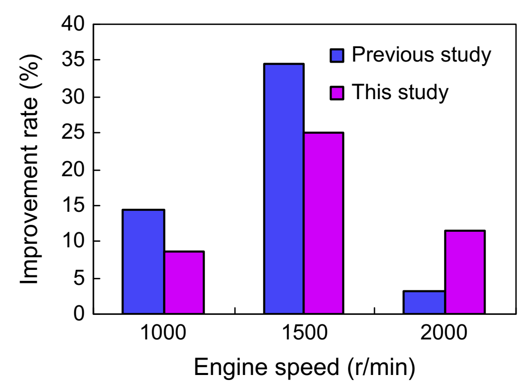


Fig. 21. Comparison of torque improvement rate [15].

the thermal efficiency of SAT engine has an increase over the ET engine, as Fig. 19 illustrates. However, compared with other parameters especially the torque, the improvement of thermal efficiency over the ET engine is very limited. More specifically, the thermal efficiency of SAT engine can only be improved by 0.6 percentage points at 1500 r/min and 0.3 percentage points at 1000 r/min. For this reason, we can say that SAT system plays a more important role in IC engine power performances than its economic performances.

In order to better demonstrate the superiorities of SAT engine, the performances improvement of SAT engine have been compared to previous studies [15]. In this paper, IC engine torque and thermal efficiency are taken as the object for comparative study. Since the IC engine type (design parameters) and boundary conditions (working parameters) in this study are different from those in the previous research, it is inappropriate to compare the improvement of torque and thermal efficiency directly. For this reason, the improvement rates of SAT engine torque and thermal efficiency have been investigated (referencing to Formula (9) and (10)), as shown in Figs. 20 and 21, respectively. Through analyzing the comparison results, some conclusions can be drawn. In the two kinds of SAT engine, the improvement rates of torque are much higher than those of thermal efficiency. Among the three speed points, both the maximum improvement rates of torque and thermal efficiency appear at the speed of 1500 r/min. At 1000 r/min and 1500 r/min, the improvement rates of torque and thermal efficiency in this study are a bit lower than those in previous study, this is caused by the IC engine design parameters and operating states, such as the target boosting pressure, turbocharger MAP. In a word, all the data show that SAT system has lots of superiorities.

4.3. Others discussions

Another interesting topic about the SAT system is to estimate the volume for the required water tank to apply this concept in a real world case. Before the raw estimation, some assumptions should be made, which are listed as follows: (1) All the low-speed operating conditions are represented by two typical speed points, 1000 r/min and 1500 r/min; (2) Automobile (or IC engine) operates at the two typical speed points (1000 r/min and 1500 r/min) for each 15 min in the driving range. Then, the volume for the required water tank can be calculated. According to the analysis above, at 1000 r/min, the steam injection amount is set to the maximum of 3.27 g/s (at the steam temperature of 700 K), for the purpose of pursuing the maximum achievable boosting pressure (which is about 1.2 bar at 1000 r/min). If the automobile (or IC engine) operates at this speed for 15 min, it requires 2.94 kg water. At 1500 r/min, the maximum steam injection amount is 7.47 g/s at the steam temperature of 700 K. According to Fig. 9(b), the steam injection amount can be set to 6 g/s (at the steam temperature of 700 K) to achieve the target boosting pressure of 1.55 bar. If the

automobile (or IC engine) operates at this operating condition for 15 min, 5.4 kg water is required. Thus, based on the above assumption, the required water in the automobile driving range is 8.34 kg. Accordingly, the volume for the required water tank should be larger than 8.34 L, which is acceptable and feasible for an automobile.

5. Conclusions

In this paper, the approach of steam-assisted turbocharging was proposed to boost IC engine intake gas pressure, and the working processes of SAT were discussed in detail though numerical calculation and parameter analysis. Based on the results and contents elaborated above, a few conclusions can be drawn as follows:

(1) SAT is a kind of compound turbocharging, since it consists of steam turbocharging and exhaust turbocharging. And it has merged the advantages of the two kinds of turbocharging approaches. Under the low-speed operating conditions, exhaust turbocharging system has poor working performances due to the low exhaust gas energy. Under the circumstances, the SAT can effectively solve this issue and show its superiority.

(2) At identical IC engine speed, the maximum steam amount generated by SAT engine exhaust gas energy changes a little with the steam temperature. On one hand, the higher steam temperature requires more exhaust gas energy for the fixed steam, which means the reduction of steam amount; on the other hand, the higher steam temperature has a positive effect on the turbine output power and then intake pressure, and finally, it results in more exhaust gas amount and also larger exhaust gas energy, which means the increase of steam amount. As a result, it is better to select a higher steam temperature for the SAT engine.

(3) After the steam is injected into the turbine inlet, the working performances of both the turbine and the IC engine are changed. Due to the increase of working medium as well as turbine efficiency, the output power of turbine is improved, and it leads to the promotion of IC engine intake gas pressure. Meanwhile, IC engine exhaust gas pressure also increases with the steam injection amount. As a result, more effective work should be consumed during the exhaust process. Owing to the increase of intake gas pressure and intake process work, IC engine pumping work only changes a little.

(4) The low-speed performances of IC engine especially the torque can be effectively improved by SAT. At 1000 r/min, due to the low exhaust gas flow rate as well as low exhaust gas energy, the generated steam is not enough to assist the turbocharging system. Under the circumstances, the IC engine intake gas pressure can only be increased by 0.1 bar or so, and the improvement of IC engine performances is very limited. With the increase of speed, the steam amount generated by SAT engine exhaust gas energy is improved, thus the effect of SAT system on IC engine turns more remarkable. At 1500 r/min, the intake gas pressure of SAT engine can reach the desired value and the torque is increased by 25.0% over the exhaust turbocharging engine. However, the thermal efficiency of SAT engine only has a slight increase, and it can only be improved by 0.6 percentage points at most at this speed.

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